SCIENTIFIC NUMISMATICS

Ancient coins have provided much information about the sites in which they were found and about the societies that produced them. They can be made to yield even more information by modern statistical methods

by D. D. Kosambi

The term "numismatics" is normally associated with the avocation of collecting coins. It is well known, of course, that the study of coins also plays an important role in archaeology. Here I should like to set forth in general terms a mathematical approach that can make numismatics more of an exact science. With this approach the archaeologist can add a degree of precision to his study of coins, and modern governments can improve the procedures with which they control their coinages and even their paper currency.

The archaeologist finds coins useful because they are normally issued by a governing authority and hence constitute a form of official document. The archaeological value of coins arises from the fact that they survive to an extent unmatched by most other documents, both because they are physically durable and because they have value for the members of the society and so are likely to be put away in hoards. As a result coins have revealed the existence of cities and even kingdoms that are not mentioned in the old literary histories.

Even when an ancient society is known from other sources, coins can be helpful in various ways. Dated coins—or those that can be otherwise identified with a particular epoch—help the archaeologist to fix the age of the level in which he is digging, to organize the chronology of rulers and to establish the dates of events commemorated by certain coins. The designs on coins reveal something of the society's religion or mythology and reflect the evolution of its art. Often the only indication of what prominent persons of ancient times looked like is provided by the portraits on coins.

FIVE-MARK SYSTEM was found on the obverse (heads) side of most coins in a hoard unearthed in 1924 in the ruins of Taxila, an ancient Indian city. In each set of five marks the first four represented a king; the fifth, an issuing authority such as a crown prince. Often the fifth mark in one set became the fourth in another, indicating that a son had succeeded his father as ruler. The marks were helpful in establishing the chronology of the coins.

This kind of information is obtained from coins by the scientific techniques of description and classification. A somewhat more complex scientific procedure involves assaying the metallic content of a coinage over a long period of time in order to obtain information about the economic history of the society. Such an investigation reveals that the French sou, which is today a synonym of worthlessness, began its career as the solidus, a gold coin of the emperor Constantine the Great [*see illustration on page 105*]. This coin's steady degeneration through 16 centuries is a considerable tale in itself. Similar work shows that the gentle art of inflation was practiced just as ably in antiquity. Plutarch says, and archaeology confirms, that Solon the Wise reduced those Athenian debts that he did not cancel altogether by making them payable in drachmas debased by 27 percent.

The mathematical approach I have in mind goes beyond the scientific procedures I have described so far. The basic theory that makes such an approach possible was developed only a generation ago. This theory, known as "the homogeneous random process," applies to numerous different types of natural phenomena that are under the influence of many factors of a random nature, for example the diffusion of molecules of one substance through the molecules of another substance, the unceasing zigzag movement (called Brownian motion) of small particles suspended in a fluid, and even the behavior of a stock exchange.

As applied to numismatics, the theory embraces several factors relating to the weight of coins. In antiquity it was easier to control the weight of coins than the alloy. The reason was that, given a good pair of balances, anyone could

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PUNCH-MARKED COINS of ancient India, similar to those found in the Taxila hoard, are depicted. On the obverse side (*left*) some features of the five-mark system shown in the illustration on the opposite page are visible. The reverse side (*right*) of such coins was either blank or carried a different system of individualistic punch marks. These coins and those in subsequent photographs are in the collection of the American Numismatic Society. In all the photographs the obverse side is at left and the reverse side is at right.

weigh the coin quickly and accurately, whereas an assay of the metallic content of the coin called for an expert. Hence the weight of a society's coinage tended to remain fixed even when the coinage was systematically debased in metallic content.

Yet no matter how carefully coins are struck in one minting, by the same craftsmen using the same technique, there is an unavoidable variation in their weight. This variation is restricted somewhat by the traditional practice of melting down the coins that fail to come within a certain margin above or below the "true" weight. The amount of tolerance allowed has been termed "the legal remedy." In India before World War II, for instance, the legal remedy was 1/200 of the weight for the standard coin: the rupee of silver alloyed with 1/12 copper and weighing 180 grains. The differences in weight of carefully minted coins can be determined only with very delicate balances.

When a coin is put into general use, it loses a tiny amount of weight whenever it is involved in a transaction. Mechanical abrasion removes a bit of the coin, and the metal is also subjected to the chemical action of various common agents, including the acids produced by the glands of human skin. In short, the coin loses weight by wear. Such losses would vary from coin to coin even if every coin were handled in practically the same way. The fact is, of course, that not every coin put into circulation at one time is handled in the same way over the years, and so the variation among coins is increased.

The net effect of all these variations

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in weight, from both minting and wear, can be dealt with by the mathematical theory of the homogeneous random process. The result of the application of this theory to a set of coins in circulation is reflected in the three curves in the illustration on page 107. The first of them, denoted *A*, is the familiar Gaussian curve of normal distribution; it reflects the fact that a group of coins minted by some uniform process has such a normal distribution of weights. The distribution is truncated because coins weighing more or less than the tolerated margin of error have been excluded by the application of the legal remedy, but in practice the resulting deviation from a normal distribution is negligible unless the minting has been singularly slipshod.

After the coins have been in circulation for a time, the curve of weight distribution is still normal but has changed shape, as is apparent in curve *B* in the illustration. The middle of the curve has moved to the right, indicating that the average weight of the coins has decreased, and the curve is flatter, showing that the variation in weight among individual coins has increased. The decrease in the average weight and the increase in the variation are each strictly proportional to the length of time the coinage has been in circulation.

As time goes on the center of the curve moves steadily to the right from the loss of weight. The average weight declines regularly because the average loss of weight is the same per unit of time, say a year. The curve becomes flatter much more rapidly, however, because the square of the standard deviation increases regularly with time. The standard deviation is the distance from the center of the curve to the point on either side where the curve begins to bend the other way. Curve *C*, reflecting a considerable period of circulation for

DATING OF HOARD at Taxila was made possible by the presence of coins such as these. At top is a coin of Alexander the Great, who invaded India in 327 B.C. At bottom is a coin of his successor, Philip Arrhidaeus, in whose brief reign few coins were issued.

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a coinage, shows the mean weight to have declined further and the variation in weight to have increased so much that only half of the distribution can be portrayed.

Thus far I have described a situation involving a single group of coins minted and put into circulation at the same time. Suppose one were to take from circulation a random sample of coins of the same denomination, alloy and mint weight but of different date. The curve showing the distribution of weight in the sample would be asymmetric with a long tail to the right, reflecting the fact that the older coins have lost more weight than the newer ones. The shape of such a curve can be calculated theoretically, given the proportion of coins of each minting together with the general rate of wear and the rate of increase in variation in weight among individual coins. These three constants cannot be predicted theoretically; they must be obtained by observation for each country and each denomination of coin.

There is one more factor that must be considered; I have termed it "absorption." Coins of a group tend to disappear from circulation in a regular way that is proportional to the number circulating, provided that the rate of disappearance is not affected by some abnormal situation. The rate of absorption is represented by a statistical law—the same law that applies in the familiar geometric progression (2, 4, 8, 16 and so on). This is also the law of absorption for radiation, the simplest law of biological mortality, the law for the healing rate of wounds and the law of growth by compound interest.

Certain conditions have to be met if these mathematical principles are to be applied successfully. The coins must have been minted accurately enough to show only a slight initial variation in weight. If this is not done, as

DEBASEMENT OF COINAGE is typified by the gradual transformation of the solidus (*top*), a gold coin of the emperor Constantine the Great, to the French sou (*bottom*). At one time "sou" referred to the five-centime piece; it now means any coin of little value.

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SLOW ACCUMULATION of coins in a hoard renders inapplicable the mathematical approach to numismatics. Such an accumulation is the "Peter's pence" collection at the Vatican, consisting of Anglo-Saxon coins such as this one from the reign of King Offa of Mercia (eighth century A.D.). Pilgrims' donations built the collection over many generations. The mathematical approach needs coins that have had comparable histories of circulation.

was often the case with ancient coins of the less valuable metals such as copper, pewter and billon (gold or silver heavily alloyed with a base metal), the effect of wear on the weight distribution is blurred. Secondly, the circulation of the coins must have been normal enough to have the proper effect. This condition usually excludes gold coins, which are often hoarded with a minimum of handling and are also likely to be clipped by owners seeking to amass a private store of gold. Finally, a sample to which the mathematical principles are to be applied must consist of a fairly large number of coins with comparable histories. Ideally they should be from a common hoard. In keeping with this condition it is useless to compare similar coins of widely divergent histories. For example, a coin of the Greek adventurer Menander, who founded a kingdom in India about 125 B.C., turned up in a bazaar at Poona in 1942 and was accepted as currency; its history was plainly different from that of Menander coins dug up by archaeologists in various parts of India or that of a specimen found in Wales.

Even if one has access to a hoard that fulfills all these conditions, it is necessary that the hoard be reasonably well preserved so as to be free of encrustations that would produce variations in weight unrelated to the variations attributable to circulation. If a hoard of coins made of a silver-copper alloy has been buried in damp soil (as happens more often than not in India), the moisture slowly draws the copper to the surface of the coins, leaving a spongy silver underneath. Some Indian numismatists have proceeded to strip away the copper on the technically impossible supposition that molten copper had been poured onto the silver to bring up the weight of the coins.

Some years ago I was fortunate enough to have access to a hoard that met all these conditions. It was a collection of about 1,150 pieces of silver found in a bronze jar that archaeologists had dug up in 1924 in the ruins of Taxila, an ancient Indian city in what is now Pakistan. The jar and the dry climate had preserved the hoard from damage. It was possible to date the hoard approximately by the presence of an unworn coin of Alexander the Great, who invaded India in 327 B.C., and to date it more precisely by a mint-condition coin of the emperor who briefly succeeded Alexander—his half brother Philip Arrhidaeus. The condition of the coin, taken together with the facts that Arrhidaeus issued few coins and that Taxila was far from his actual domain, justifies the assumption that the coin found its way into the jar soon after issue. The hoard can thus be dated close to 317 B.C., when Arrhidaeus was imprisoned and assassinated. There was nothing in the archaeological context to indicate that the hoard had been deposited slowly over a long period of years, as is the case with religious deposits such as the "Peter's pence" collection at the Vatican, consisting of donations left annually by generations of Anglo-Saxon pilgrims. Therefore it seemed reasonable to assume that the Taxila coins had had a comparable history of circulation and that this history had come to an end at about the time Alexander's local successor Seleukos Nikator lost Taxila to an invading army from the east.

Beyond this the coins at first yielded little information. Most of them had on their obverse (heads) side five punch marks with much in common from coin to coin. The reverse (tails) side in many instances had an entirely different system of much smaller punch marks. Nothing else was readily evident. The hoard therefore presented a difficult problem of classical numismatics: the arrangement of unidentifiable coins in their proper chronological order. It was in addressing myself to this problem that I began to work out the application to numismatics of the mathematical principles I have described.

By way of background to the story of my investigation it will be useful to describe briefly the historical setting of India in the period to which the hoard is ascribed. Alexander, whose army was reluctant to follow him farther in his effort to conquer Asia, retreated from India soon after invading it. After his departure a Hindu king, Chandragupta (called Sandrocottus in Greek records), extended his rule over the entire northern part of the Indian subcontinent, expelling or destroying the Alexandrian garrisons. Chandragupta established the seat of his empire at the capital of the kingdom of Magadha in what is now the Indian state of Bihar. Thus was founded the dynasty called Maurya, which lasted from 312 to 178 B.C. The most illustrious figure of the Mauryan dynasty was Chandragupta's grandson Asoka, who reigned for many years, expanded the empire as far west as the Greek kingdom of Bactria and by supporting Buddhism gave it a powerful impetus in India.

In the immediate pre-Mauryan period the only royal authority strong enough to issue coins on a large scale was the Magadha kingdom. In fact, it is evident from a comparison of the punch-marked coins of the Taxila hoard that they are of the type found in profusion in Magadha and wherever Magadhan influence penetrated. The system of five marks on the obverse side of the Taxila coins is the same as that of the Magadhan royal coinage [*see illustration on page 102*]. The first four marks represent a king; the fifth, an issuing authority such as a crown prince or provincial governor. Often the fifth mark in one series becomes the fourth in another, indicating that a son had succeeded his father.

These marks made it possible to group the coins. Then the average weight of each group gave its relative chronological order. It might also be thought that the marks would make it possible to

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set each marking system opposite the name of a king and thereby solve the whole problem of chronology. The difficulty here lies with the limitations of Indian historical records. There are no known or decipherable royal inscriptions before Asoka. The records of the Jains, the Buddhists and the Brahmans often call the same kings by different names. In any case the names of kings usually appear in such records almost incidentally, as part of the inflated, semimystical story of some religious figure such as the Buddha. There is no mathematical theory for this kind of history.

Considerably more useful were the punch marks on the reverse side of many coins. These marks, unlike those on the obverse side, bore little resemblance to one another. They showed all the individuality of the ticket punches used by conductors on American railroads. A group of coins with identical obverse markings might include some specimens with blank reverse sides and some with from one to more than 20 of the tiny reverse marks. (When the number rose above 20, the marks were difficult to count.)

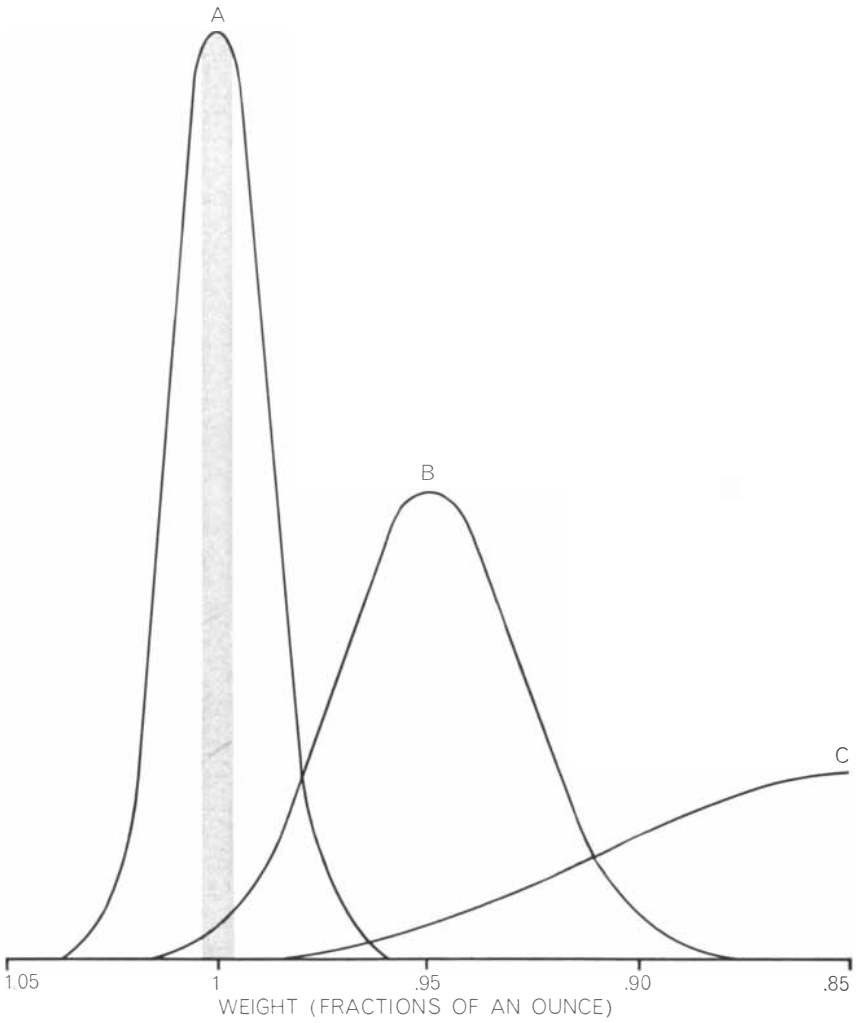
If one ignores the obverse side and merely groups the coins according to the number of marks on the reverse, a striking fact emerges: the larger the number of marks, the lower the average weight of the coins [*see illustration at left on next page*]. In other words, the reverse marks supplement the loss of weight as a sign of age. Evidently the reverse marks were correlated in some systematic way with the circulation of the coins.

These marks indicate a system of regular checking of the coinage, probably by traders' guilds. The traders were simultaneously financiers, bankers and dealers in precious metals; they would have had good reason to assure themselves that a given coin continued to adhere to a standard of weight. Presumably the checking was done at more or less regular intervals, apparently about every 12 years, indicating that the practice began about 500 B.C.

Both the obverse and the reverse marks were valuable as corroborative evidence when I undertook to check the weight, variation and absorption rates of the Taxila coins. Interestingly enough, about 95 percent of the coins fell in the range of some very accurately cut stone weights found in the excavations of two cities much more ancient than Taxila: the cities of Mohenjo-Daro and Harappa in the valley of the Indus River. This great civilization, comparable to that of Sumer and probably contemporaneous with it, had vanished without apparent trace until it was revealed by digging in 1925. Yet in spite of the complete silence of all Indian tradition on the existence of the earlier civilization the weight standard of the Indus valley survived unchanged into Mauryan times.

The weight curve of the Taxila hoard has the expected distribution with a tail to the right. Moreover, the number of coins compared with the number of reverse marks follows closely the theoretical "absorption" curve [*see illustration at right on next page*]. About 70 percent of the coins survived after each checking period, however long that period was. These observations suggest two things about the economy of Taxila: (1) it was stable for more than 200 years, as indicated by the regularity of circulation reflected in the curves of weight loss and absorption of the coinage, and (2) the balance of trade ran in favor of Taxila, as indicated by the presence of Magadhan coins in the community—coins that could only have come in payment for goods originating in or shipped through Taxila.

The same Taxila mound in which the hoard I have described was found yielded another hoard that was deposited at a higher level and hence was associated with a later time. The coins looked cruder. The system of obverse marks remained but the reverse marks had disappeared. Although these coins were almost in mint condition, the variation in weight was decidedly larger than that in the blank-reverse (and therefore little-used) coins of the earlier



DISTRIBUTION CURVES depict the history of circulation of a group of coins carefully minted and put into circulation at the same time. Curve *A* is high and narrow, indicating that most of the coins (a preponderance represented by the gray band) are close to the "true," or mean, weight. After a period of circulation (*B*) wear has caused the mean weight to decrease and the variation in weight from coin to coin to increase, an increase shown by the flattening of the curve. Further circulation augments these effects (*C*): mean weight is lower and variation has increased so much that only half of the distribution is shown.

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hoard. In addition, the alloy was notably debased.

This second hoard was dated to about 250 B.C. by a coin of the Greek king Diodotus I, king of Bactria. Thus the punch-marked coins of the hoard were contemporaneous with Asoka. Although his coins had never been identified until these new methods pinned them down, it was known that his empire was prosperous and spread over the whole of modern India and Pakistan and most of what is now Afghanistan. The architecture and sculpture of the age were outstanding. Why, then, should the coinage be crude? Was there perhaps some mistake in my theoretical approach?

I was able to answer these questions by considering Indian currency that was in circulation in 1940 and 1941. At that time the rupee was still silver, but its copper content had been raised from a twelfth to a half. Moreover, the legal remedy had been abandoned. Although the same mints and machines had fabricated both prewar and wartime coins, I was able to pick out new rupees in 1941 that were above the standard weight by more than twice the old tolerance limit. Obviously Asoka's empire had been short of currency for everyday use, as the government of India was during World War II. Silver currency in both periods was progressively debased, although the ancients—unlike the wartime regime of India—never resorted to tokens and had no paper currency.

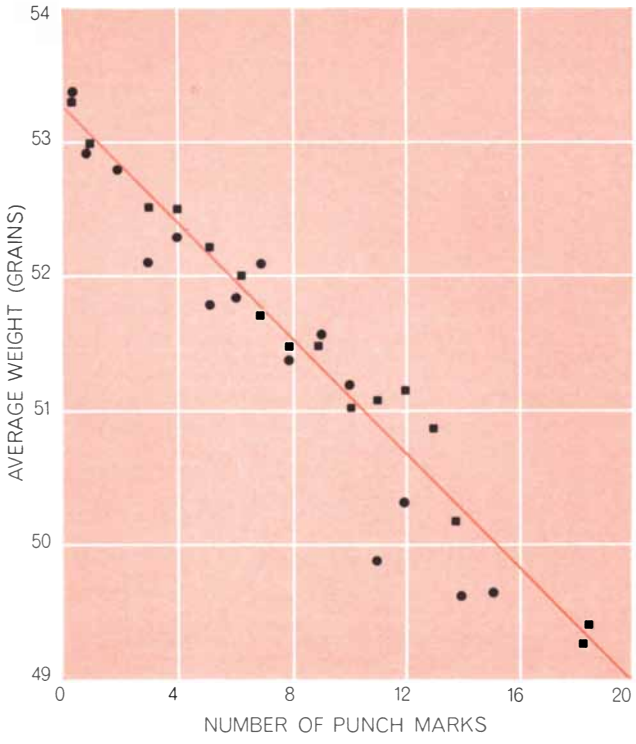
Having developed my idea of applying mathematical theory to the study of coins, I tested it with coins that were circulating in India in 1940 and 1941. Much of this work was drudgery; it took me about three minutes to weigh each of some 7,000 coins on a slow analytical balance. The tedium was somewhat relieved by the fieldwork involved in obtaining a representative sample of coins from active circulation. Except in three readily explainable cases, the weighings produced curves that closely fit the theoretical curves.

The first exception had to do with gold sovereigns. They had not been legal tender since 1931, although they did change hands occasionally between hoarders. Even so the fit would have been good had it not been for the two oldest pieces, which had been used only for worship by the family that lent them for weighing. Placed in front of the family's image of Lakshmi, the goddess of wealth, the two sovereigns had remained untouched for two generations.

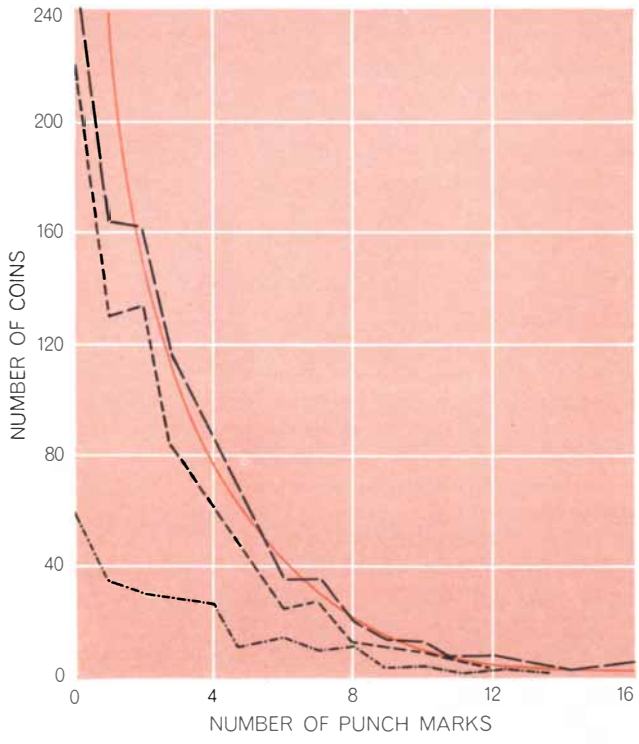
Another exception was the humble copper pie, which was then worth 1/192 rupee and could be found only in a few places such as Benares, where pilgrims distributed them as "charity" to beggars in order to gain merit at the lowest possible cost. The friend who had supplied me with 1,000 pie coins did not have the patience to take them all from the marketplace; he supplemented those that had been in regular circulation with a large number from a bank vault, where they had lain unused for years.

Thirdly, the anna pieces were of soft metal and in common use. Hence they wore more rapidly than any other Indian currency. Wear made it impossible to read the dates on some of the annas, and these pieces had to be removed from the sample. They were the most worn and therefore the oldest coins; they were also the lightest, and their removal from the sample raised the average weight of the rest of the sample.

The mathematical approach to numismatics has applications beyond archaeology. In this age of vending machines, pay telephones, turnstiles and whatnot the rate of wear of metal cur-



AGE AND WEIGHT of coins in the Taxila hoard are closely correlated. The punch marks were put on the back of the coin periodically for checking purposes; hence the more punch marks, the longer the coin was in circulation. The average loss of weight of the coins, resulting from wear, is shown by the diagonal line. Square and round symbols represent square and round coins.



ABSORPTION OF COINS, meaning their loss from circulation for various reasons, shows a close correlation with the number of punch marks found on the reverse side of the coins in the Taxila hoard. The theoretical curve of absorption is shown in color; the broken curve closest to it represents all the punch-marked Taxila coins. Other curves represent square and round coins in the hoard.

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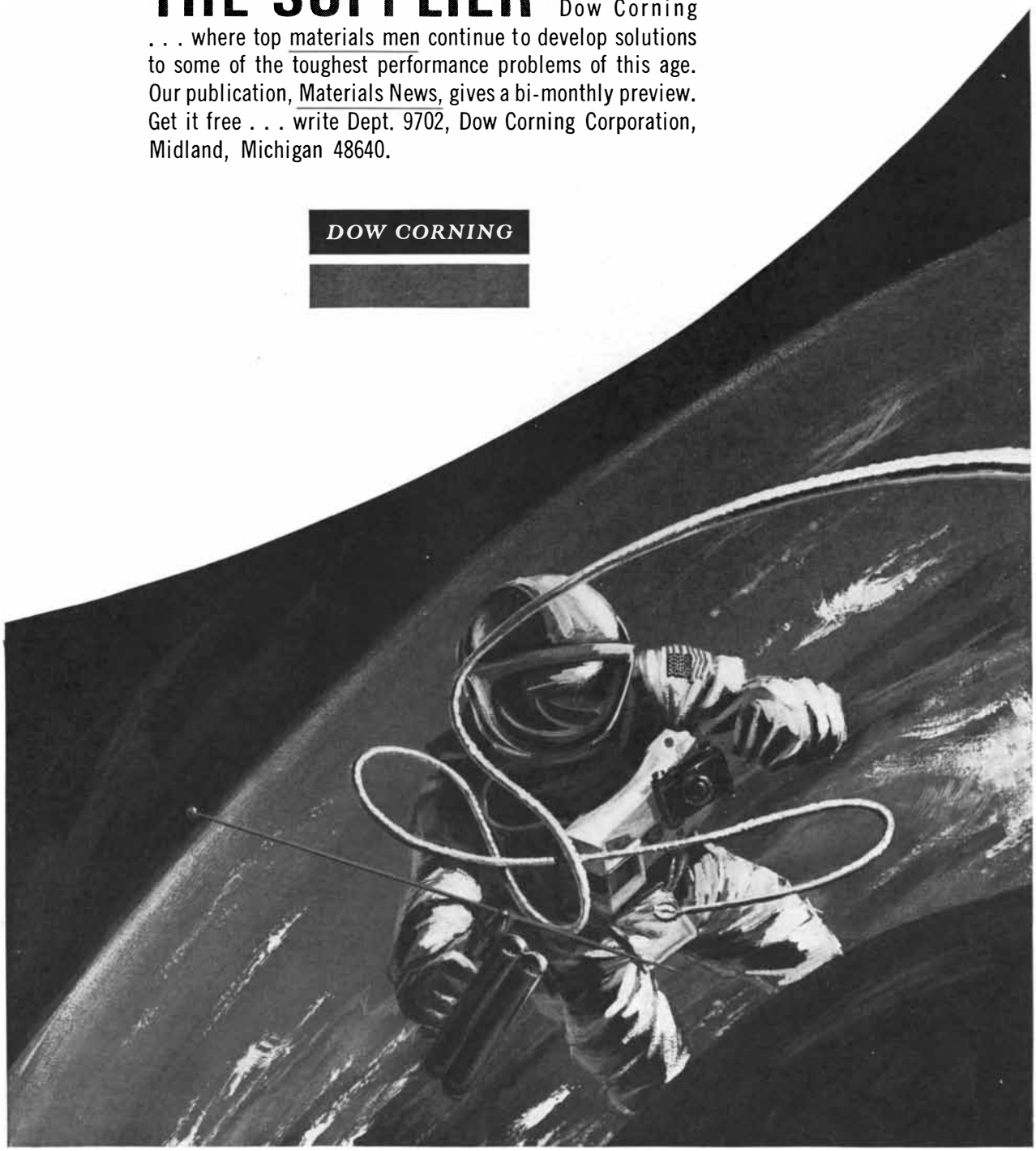

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SECOND TAXILA HOARD was dated approximately by the presence of a coin such as this one from the reign of Diodotus I, who was king of the Greek kingdom of Bactria in about 250 B.C. Hence the second Taxila hoard was deposited about 75 years after the first.

rency could readily be determined by weighing samples, preferably on a much larger scale than my own modest efforts. Given the rates at which weight decreased and variation increased, and the weight limit below which a coin would be regarded as useless, the rate of replacement for every denomination could be calculated and the necessary replacement coins minted on a systematic schedule. Allowance would have to be made for changes in demand, such as those resulting from new consumer products and from population growth, and for loss of coins.

A second application would be to keep track of the number of coins in active circulation. This can be tested by the same procedure used to estimate the fish population of a lake. The fish are caught in a net, tagged and thrown back. The number of recaptures is plotted against the total catch; a simple formula then allows a calculation of the population. This number, of course, represents not all the fish but all the fish that are susceptible to the particular method of capture.

The "netting" of coins could be done by sampling post offices, banks, vending machines and stores on a certain day throughout the country. Tagging might be done by making the coins harmlessly radioactive. Then the recapture could be detected by a Geiger counter. A similar procedure would make it possible to estimate the amount of paper currency in active circulation. The tagging could be done through the serial number, which a computer would read by electronic methods. The same computer would be programmed to provide an estimate of the total currency in circulation. By these methods a scientifically minded treasury could decide on the basis of wear and loss whether it was better to issue coins or paper for any given denomination.

COIN OF MENANDER, a Greek who founded a kingdom in India around 125 B.C., is shown. A similar coin turned up in the marketplace at Poona in 1942 and was accepted as currency. Such a coin could not be used in a mathematical approach to numismatics because it would have a history of circulation widely divergent from that of other coins of similar origin.

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